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A Rain Simulator for Greenhouse Use

Anna W. Schoettle and Robert Hubbard[1]

A system is described that can be used to deliver simulated acid rain to potted plants to test for effects of altered rain chemistry or duration. The system consists of a water purifying unit, holding tanks where the chemistry of the water can be altered, and stalls containing spray delivery units. The system was tested for uniform water delivery and droplet size. The recipe for formulating a rain solution similar to the ambient rain chemistry in the central Rocky Mountains is included as well as a suggested method to augment the rain solution to simulate acid rain solutions.

Keywords: Acid rain, droplet size, rain chemistry, simulated rain, water purifiers, spray nozzles.

Introduction

Effective prediction of the potential effects of acid rain on plants requires dose-response studies where the rain chemistry can be manipulated in a controlled manner, applied to plants, and the effects monitored. Such studies are difficult to conduct in the field because of the need to protect the vegetation from ambient rain and to deliver the test rain solutions to the plants in a natural way. Screening plants for possible responses to different rain chemistries is much more economically conducted in controlled environments. A rain simulator for use in a greenhouse must be constructed such that 1) the rain chemistry can be easily manipulated, 2) the components of the system will not react with the rain chemistry, and 3) the system can deliver simulated rain in a consistent, controlled manner. Greenhouse experimentation enables potential effects to be identified and examined in statistically valid designs. The results from greenhouse experiments can then be applied to design efficient studies for field verification.

We present the design specifications for a simulated rain delivery system for construction in a greenhouse. We have used some of the techniques used by others (Chevone et al. 1984, Jacobson et al. 1986) as well as some new components and testing procedures to provide an economical, versatile, and reliable rain simulator. We also present a recipe for mixing a simulated rain solution to mimic the ambient rain chemistry in the central Rocky Mountains during the mid-1980's, and a method to augment that solution to produce simulated acid rain for use in plant studies.

[1]*Research Plant Physiologist and Ecologist, respectively, with the Rocky Mountain Forest and Range Experiment Station. Headquarters is in Fort Collins, CO, in cooperation with Colorado State University.*

Construction Specifications

The rain simulator described here consists of a water purifying unit, mixing tanks, and spray delivery stalls (fig. 1). The water purifying system supplies reagent-grade deionized water to four mixing tanks. In the mixing tanks the chemistry of the water can be adjusted to the desired compositions. The simulated rain is then passed through inert pumps to four stalls, each equipped with a nozzle system that delivers the water to rotating platforms which hold the target plant material. The four rain stalls can treat four groups of plants simultaneously with the same or different rain treatments.

Water System

The reagent-grade water is supplied by passing tap water through a reverse osmosis (RO) deionizing unit from Culligan Water Systems (Northbrook, IL).[2] This unit supplies water that has a conductance of no greater than

[2]*The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.*

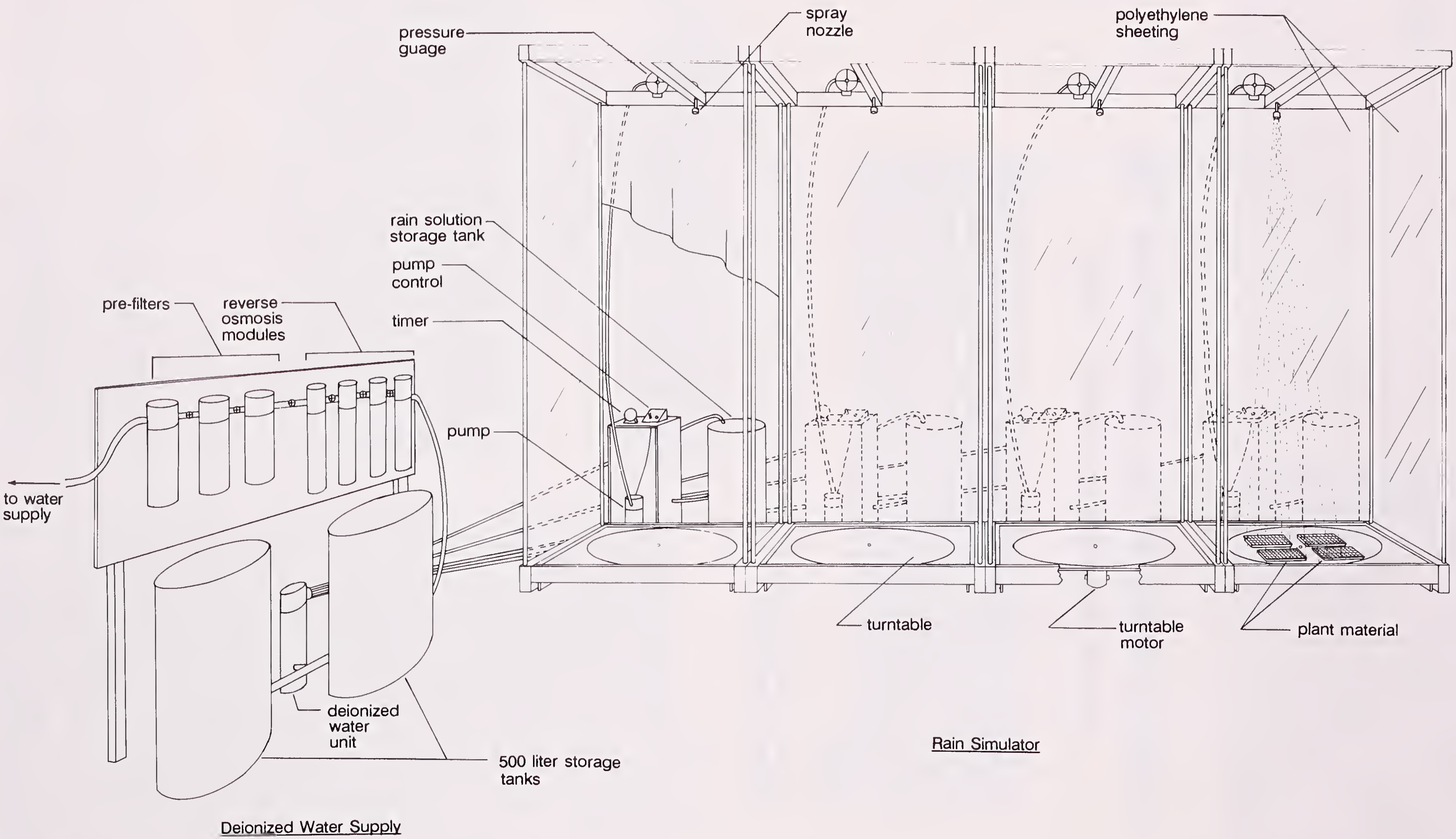

Figure 1. Schematic diagram of the greenhouse rain simulator.

18 megohms, and has a generating capacity of 15 L per hour. This unit was built specifically for our rain simulator, but any system that meets these specifications can be used.

Tap water passes through three prefilters (two 5-micron and one carbon) before being pumped through four reverse osmosis modules (#4493–72(8SP)) in series. The deionized water is then stored in two 500-L polyethylene storage tanks (Kerrco, Inc., Hastings, NE), one of which is equipped with a level controller (Meyers #ALC18P) to facilitate filling without supervision. When needed, the deionized water is repressurized and pumped through two 3000 grain capacity deionizing modules and passed into four 120-L polyethylene holding tanks (Nalgene). The water in each tank can be treated at this stage to yield the desired rain composition.

Delivery System

Each holding tank is equipped with a magnetic-drive gear pump (Micro Pump System #J-7003-04) equipped with interchangeable heads that allow for versatility in achieving specific flow rates. The wetted portions of the pumps are graphite and Teflon, neither of which react or corrode with most rain chemistries. Each pump is controlled by a variable-speed controller (Cole Palmer #7144–04) and a timer (VWR #62363–003). The flow rates exiting the pumps are monitored by Marshall Town gauges and are maintained at 25 psi. The 1/4-inch polyethylene tubing delivers the simulated rain solution to a hollow cone nozzle (Delavan Delta Corp. #RA-2) mounted within a 1 by 1 by 2.5 m three-sided stall made of polyethylene sheeting. The stalls prevent drift between treatments and minimize any draft effects on droplet size. Within each stall the nozzle is mounted 2 m above the edge of a 0.9-m-diameter turntable. The turntable is made from 3/4-inch plywood treated with waterproof enamel, mounted on a small 6-rpm motor (W.W Grainger #3M104–0). The potted plant material can be placed on the turntables during the treatment period, and rotated to ensure uniform distribution of simulated rain to the plant material.

Testing and Calibration

Rainfall Distribution

To determine if the simulated rain solution was evenly distributed over the surface of the turntable, thirteen 50-mL beakers were placed crosswise across the diameter of each turntable. The line pressure prior to the nozzles was adjusted to 25 psi. The water delivery system and the turntables were activated for 1 hour, the volume of water in each beaker was measured, and the deposition rate per hour per area was calculated. The amount of water delivered to each of the four turntables was compared by analysis of variance (SPSS). The deposition rate of water did differ between stalls ($p > 0.05$) (table 1). The maximum difference in deposition rate between stalls was 12%. The average deposition rate of water was 0.86 cm per hour. This rate is comparable to those achieved by others for simulated rain systems (Chevone et al. 1984, Jacobson et al. 1986). Because of the differences between stalls, we recommend that the treatments be rotated through the stalls during an experiment rather than maintaining a treatment in a given stall. The outside edges of the turntables received slightly more water (2–5%) than the middle of the surface. This difference was statistically significant (ANOVA, $p < 0.05$); therefore we also recommend that the plants be consistently placed on either the edge or the middle of the turntables.

Droplet Size

To determine the size of the droplets delivered to each turntable in each stall, we placed one beaker of liquid nitrogen on the edge of the turntable and another in the center of the turntable. The rain delivery system and turntables were activated, and droplets were collected for 1 minute. The diameters of thirty droplets (ice spheres) from each container were measured with an ocular micrometer on a dissecting microscope in a cold room. There were no significant differences ($p > 0.05$) in droplet size between stalls or positions on the turntables within stalls. The average droplet size was 0.704 mm with a standard deviation of 0.170 mm, which is comparable to the droplet sizes obtained by others (Jacobson et al. 1986). This method of measuring droplet sizes of rain may slightly overestimate the actual size of the water droplets because the droplets expanded during freezing.

Simulated Rocky Mountain Rain

Rain chemistry data from Lock Vale, Rocky Mountain National Park, Colorado were obtained for June through September of 1984 and 1985 (NADP Annual Reports). The average ionic composition of the ambient rain water is shown in table 2. This rain chemistry can be simulated by adding laboratory chemicals to deionized water. The simulant is mixed to form a 1:1,000 concentrate which can be further diluted to make the simulated rain solutions. The recipe for the concentrate is shown in table 2.

The concentrate can be stored at 4°C for no longer than a week. Before preparing the concentrated simulant, diluted acid solutions should be made. These solutions can be stored at 4°C for several weeks. The diluted HNO_3 solution (1:100) is prepared by adding 10 mL of concentrated acid to deionized water and adjusting the

Table 1. Average deposition rates of simulated rain in each of the four stalls.

Replicate	Deposition rate (cm/h) Stall 1	Stall 2	Stall 3	Stall 4
1	0.80	0.78	0.88	0.88
2	0.78	0.75	0.85	0.89
3	0.81	0.80	0.88	0.92

Table 2. Average ionic composition of ambient rain from Rocky Mountain National Park, Colorado for June through September (1984 and 1985), and the recipe for preparation of the rain solution (simulant) of the same ionic composition.

AMBIENT RAIN		SIMULATED RAIN	
Ion	Concentration (mg/L)	Compound added	1:1,000 concentrate (g/L)
Ca^{++}	0.508	$CaCO_3$	0.619
Cl^-	0.23	$CaCl_2 \cdot 2H_2O$	0.724
Mg^{++}	0.081	$MgSO_4 \cdot 7H_2O$	0.822
$SO_4^=$	1.66	K_2SO_4	0.183
K^+	0.083	$NaNO_3$	0.447
Na^+	0.121	$(NH_4)_2SO_4$	1.064
NH_4^+	0.29	H_3PO_4	0.005
PO_4^-	trace	HNO_3 [a]	139 ml
NO_3^-	1.68	H_2SO_4 [b]	266 ml

[a] *1:100 dilution of concentrated HNO_3.*
[b] *1:1000 dilution of concentrated H_2SO_4.*

Table 3. Recipe for diluting the concentrated rain solution to make simulated ambient rain and acid rain solutions containing 10, 30, and 50 times the nitrate concentration in the ambient rain solution. Table values are the amount of the concentrated solution to be added to each 1 L of simulated rain.

Rain Solution		Amount to add to deionized water to make 1 L of simulated acidic rain	
x amb. NO_3^-	pH	1:1000 ambient rain concentrate (mL)	1:100 dilution of HNO_3 (mL)
Ambient	4.9	1	0
10x	4.2	1	1.45
30x	3.5	1	5.00
50x	2.9	1	8.44

total volume to 1 L in a volumetric flask. The diluted H_2SO_4 solution (1:1,000) is made by adding 1 mL of concentrated sulfuric acid to deionized water and bringing the volume up to 1 L. A 1-L volumetric flask should also be used when preparing the concentrated rain stimulant. To insure the solubilization of the $CaCO_3$, it should be added to the volumetric flask with the 139 mL of diluted HNO_3 before the other ingredients. This mixture should be swirled until the $CaCO_3$ is completely dissolved. The other ingredients can then be added with deionized water to make a total volume of 1 L. To mix the actual rain solution, 1 mL of this concentrated rain simulant should be added to deionized water to make each liter of simulated ambient rain solution. This will yield a rain chemistry that simulates the ambient rain chemistry in Rocky Mountain National Park during the summers of 1984 and 1985 with a pH of 4.9.

The simulated ambient rain can be augmented with additional amounts of nitric, sulfuric, or hydrochloric acid alone or in combination to make simulated acidic rain solutions. Table 3 shows how much nitric acid must be added to the simulated ambient rain (the actual rain solutions, not the concentrated rain mixture) to generate simulated rain solutions that contain 10, 30, or 50 times the nitrate levels of the ambient rain solution with a pH of 4.2, 3.5, or 2.9 respectively. To prepare these simulated acidic rain solutions, we add additional amounts of the same diluted HNO_3 solution (1:100) that we first mixed, to the ambient rain solution after it has been diluted to the actual rain concentration.

Summary

We have described a rain delivery system that can be easily constructed within a greenhouse for plant studies. The rain solutions can be adjusted to the desired composition and delivered to plants in a relatively natural manner. This system enables the study of the effects of rain composition, duration, or both on plants in the controlled environment of the greenhouse.

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